Scan Angle Dependent Radiometric Modulation due to Polarization for the Atmospheric Infrared Sounder (AIRS)

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ABSTRACT

Space based remote sensing instruments employing scanning mirrors to acquire data on the earth can experience a radiometric modulation with scan angle (striping) due to polarization effects. Mirrors inherently introduce polarization that depends on the angle of incidence and orientation of the mirror. In the case of the Atmospheric Infrared Sounder (AIRS) the angle of incidence is constant, however the orientation of the mirror changes with scan angle. The polarization of the scan mirror couples with that of the aft optics which is highly polarized due to use of a diffraction grating for spectral separation to produce a radiometric modulation with scan angle. This modulation must be considered when calibrating the radiometry of the instrument.

Data acquired during instrument testing on the polarization of the spectrometer were combined with data obtained for the scan mirror to model the expected radiometric modulation. Results were compared with direct measurements of the modulation obtained during radiometric testing while viewing a large area blackbody. Agreement is very good and shows that the modulation is very small and can be modeled to an accuracy consistent with the radiometric calibration budgets. Both modeled and measured results are presented for representative bands in the instrument as well as a discussion of the modeling techniques and equations used, and a discussion of the test data and the conditions under which it was obtained.

1. EOS, AIRS, Polarization, Radiometry, Remote Sensing, Striping

1. INTRODUCTION

The Earth Observing System Aqua spacecraft to be launched in early 2001 host the Atmospheric Infrared Sounder (AIRS). AIRS is designed to measure atmospheric water vapor and temperature and includes 2378 infrared spectral channels from 3.75μm to 15.4 μm (reference 1). AIRS was developed by Sanders Infrared Imaging Systems, a Lockheed corporation, under Contract ~~management~~ by Cal-Tech JPL and is currently undergoing spacecraft integration at the TRW Redondo Beach facility. The AIRS scan mirror rotates about an axis that is 45 degrees from the mirror normal. This preserves the angle of incidence of the mirror and the optical axis at 45 degrees and allows the Earth scene energy to be scanned over a range of ±49.5°. The AIRS scan mirror introduces a small amount of polarization to the reflected radiance. As the scan mirror rotates, the mirror polarization couples with the polarization of the AIRS spectrometer and produces a small radiometric offset that is scan angle dependent. We discuss here this radiometric offset and how it is determined through various measurements and modeling.

2. THEORY

The true scene radiance will then be the sum of the derived radiance using the calibration coefficients at nadir plus a correction term that is scan angle dependent.

$$N_{true} = N + dN_p(\delta) \tag{1}$$

We have calculated the radiometric correction term, dN_p, to be

$$dN_p = p_r p_t \left\{ N\left[\cos 2(\delta-\alpha) - \left(1 - \frac{2N_s}{N_c}\right)\cos 2\alpha\right] - N_s\left[\cos 2(\delta-\alpha) + \cos 2\alpha\right]\right\} \tag{2}$$

where

δ = angle relative to space view = Scan angle + 90 degrees (derived from telemetry)
α = phase of the polarization of the spectrometer (measured pre-flight)
p_r = polarization of the scan mirror (measured pre-flight)
p_t = polarization of the spectrometer (measured pre-flight)
N_s = radiance of a unity emissivity blackbody at the temperature of the scan mirror (from telemetry)
N_c = the radiance of a unity emissivity blackbody at the temperature of the On-Board Calibrator (OBC) (from telemetry)
N = the radiance of the scene (derived from the signal dn and the radiometric calibration coefficients obtained a nadir)

The radiometric correction therefore needs to be calculated and applied for every footprint of every channel of every scan. The correction is to be added to the radiance derived from signal (dn) in the standard Level 1B calibration equation.

3. MEASURED POLARIZATION DATA

Data were obtained during system level testing in Thermal Vacuum of the AIRS instrument polarization (reference 2). An off-axis section of a paraboloidal mirror is used to project the image of a target aperture onto the field stop of the AIRS Instrument. The projected target image is large enough to overfill the AIRS field stop. The target aperture at the focus of the collimator is back illuminated with a black body source reflected from a spherical condenser mirror. The polarization of the optical beam entering the AIRS entrance pupil has four possible states, selectable by a choice of one of four positions of a filter wheel containing wire grid polarizers in three different orientations, plus one open position. The filter wheel is in close proximity to the target aperture, reducing the clear aperture requirements on the polarizers. The polarizers and the targets are actively cooled with liquid nitrogen to a temperature less than 150 K to reduce the effects of thermal background signal on the polarization measurements.

The polarization response of the Spectrometer is determined by measuring the detector output signal corresponding to that spectral sample when each of the three polarizers are inserted into the beam, and then calculating the polarization factor and phase (the orientation of the polarization ellipse) from the data. This calculation of the polarization factor and phase employs a data reduction algorithm described in this reference 2.

Figure 1 shows the measured polarizations obtained during T/V testing. The measured data show very good correlation with a bottoms up theoretical calculation of the polarization. The theoretical polarization is based on component measurements of S and P transmission and reflection made on witness samples during the development phase. Grating polarization was calculated using a numerical electromagnetic model. Mirror data were obtained from MIT Lincoln Labs (reference 3) The system polarization model uses these data in a Mueller matrix formalism to arrive an overall determination of the system polarization. We do see some departure in the longer wavelengths from the theory. We believe this is due to the increased uncertainty in the measured component polarization in this region.

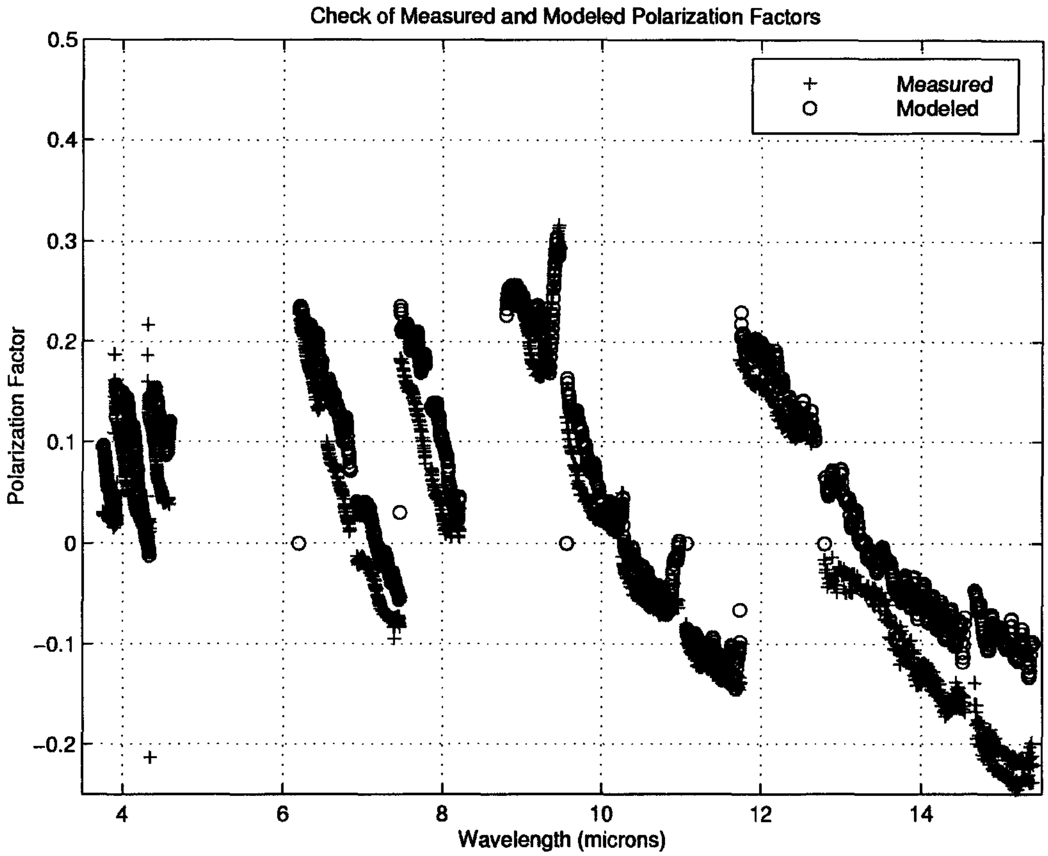

Figure 1. Measured and modeled polarizations for the AIRS instrument.

Figure 2 shows shows the scan mirror polarization data obtained from MIT Lincoln Labs and the derived spectrometer S and P transmission. The transmission of the spectrometer is based on the bottoms up model, but corrected for the measured polarization of the system. It is this coupling of the scan mirror polarization and the spectrometer polarization as the orientation of the scan mirror changes that produces the scan angle dependent modulation. These data were used in the modeling of the scan angle dependent radiometric offset.

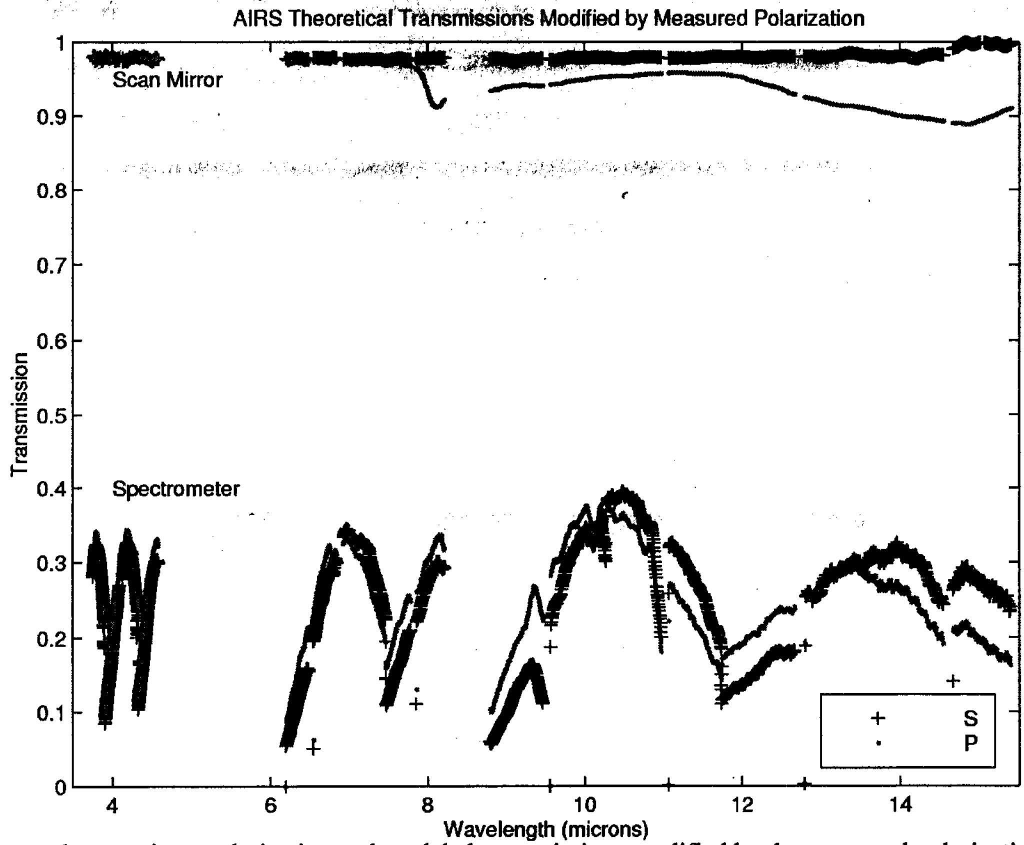

Figure 2. Measured scan mirror polarization and modeled transmissions modified by the measured polarization.

4. MEASURED SCAN ANGLE DEPENDENT RADIOMETRIC CORRECTION TERM

Measurements were obtained on the AIRS scan angle radiometric response in its final flight configuration. The AIRS instrument was allowed to view the Large Area Blackbody (LABB) at scan angles from about −48° to +36°. The radiometric offset was calculated as the difference between the radiance as derived using the internal On-Board Calibrator Blackbody (OBC), and the known radiance of the LABB.

$$dN_{p,meas} = N_{calc} - N_{calc,nadir} \tag{3}$$

The derived (calculated) radiance for the LABB from the AIRS measured digital number was obtained using the measured dn's and averaging over all scans:

$$N_{calc} = N_{OBC} \bullet \frac{\frac{1}{Nscans} \sum_{i=1:Nscans} (dn_{LABB,i} - dn_{SPACE,i})}{\frac{1}{Nscans} \sum_{i=1:Nscans} (dn_{OBC,i} - dn_{SPACE,i})} \tag{4}$$

where

dN_{p_meas} = Measured Polarization Offset
N_{calc} = Derived radiance of theLABB (W/m^2-sr-µm)
dn_{LABB} = Signal measured while viewing the LABB
dn_{SPACE} = Signal measured while viewing the space

The fractional radiometric correction and temperature correction were then calculated from the radiometric offset.

$$R = \frac{dN_{p\ meas}}{N_{calc}} \quad \Delta T = \frac{dN_p}{\partial N / \partial T} \tag{5}$$

1. CORRELATION OF MEASURMENTS AND THEORY

Results for the theoretical temperature correction vs scan angle for the center channel of each of the longest wavelength modules is shown in Figure 3 along with the results of the measurement described in the previous section. The model agrees well with the measurements for most cases except the 13.3 μm where the correction is smaller than expected. The model agrees to within the uncertainty budget and we will continually improve the results with further analysis.

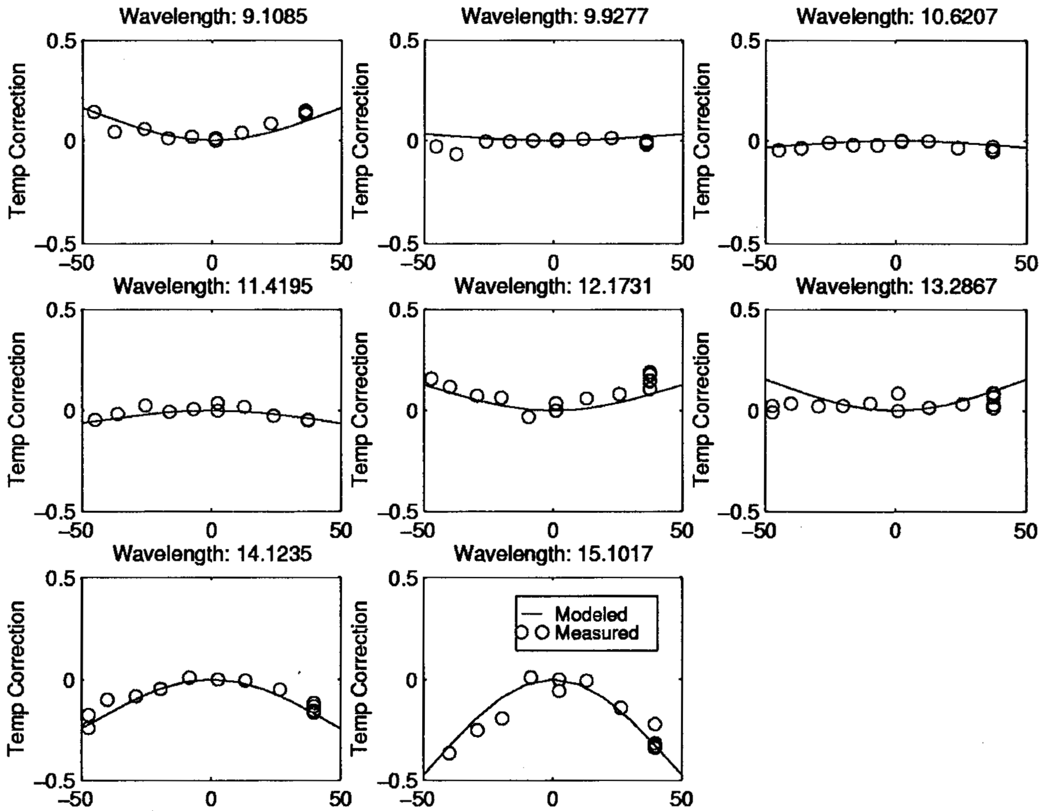

Figure 3. Scan angle dependent radiometric offset for the longest wavelength center module reference detectors.

We performed the analysis on the 51 reference detectors (center and 2 ends of the 17 IR modules) at –50 degrees. The results are shown in Figure 4. The good correlation between measurements and model suggest low residual errors. Residual errors from the model and measurements are mostly less than 0.1K with a few exceptions on the order of 0.2K. The corrections are expressed in terms of temperature and radiometric percentage of the signal flux at 250K.

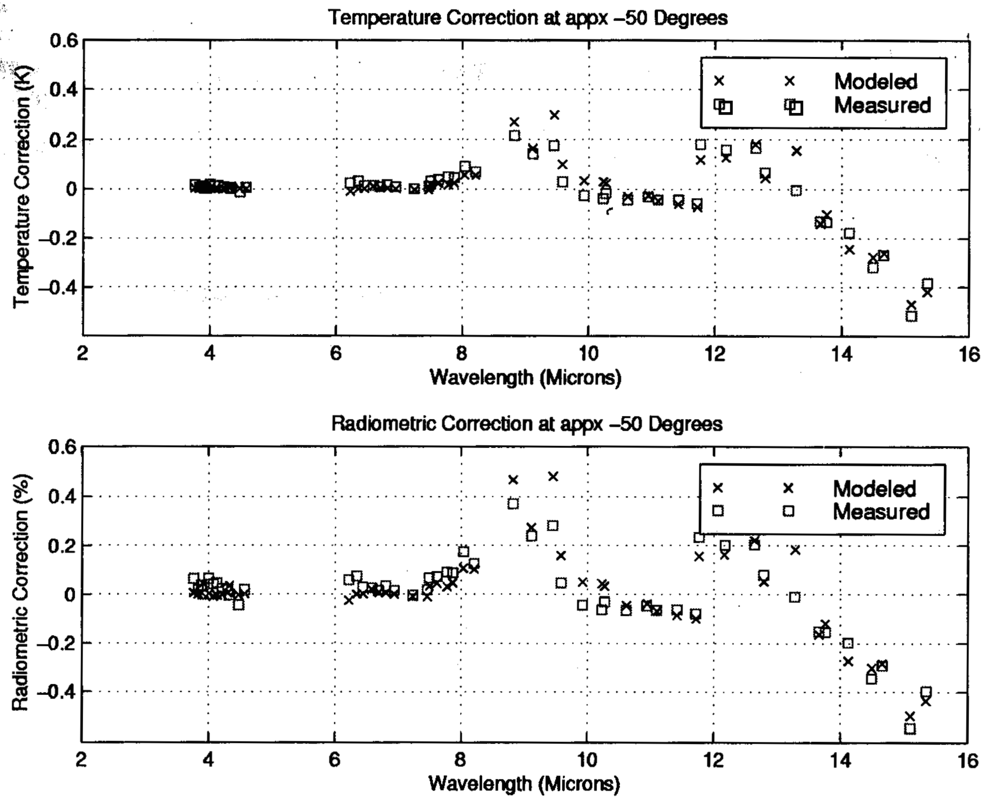

Figure 4. Radiometric offset at –50 degrees (compared to nadir) for the 51 reference detectors.

SOURCE TEMPERATURE DEPENDENCE

We observed that the radiometric response (linearity) of the AIRS at higher angles of incidence was not the same as that at nadir. There was some concern that the LABB may be vignetting at these large angles of incidence. Also that the response was not the same for different source temperatures. Here we show that the differences can be explained by the scan angle dependent radiometric polarization effect. The same theory and measurement techniques as described above were applied. Figure 5 shows the results for all channels in the measurement and the 51 reference channels in the theory. We see good correlation for the higher temperatures (within about 0.1K), but at lower temperatures, there is more noise in the measured data and more deviation with the model, particularly around 12 microns. The encouraging part of these results is that the model follows the change in behavior vs wavelength and temperature.

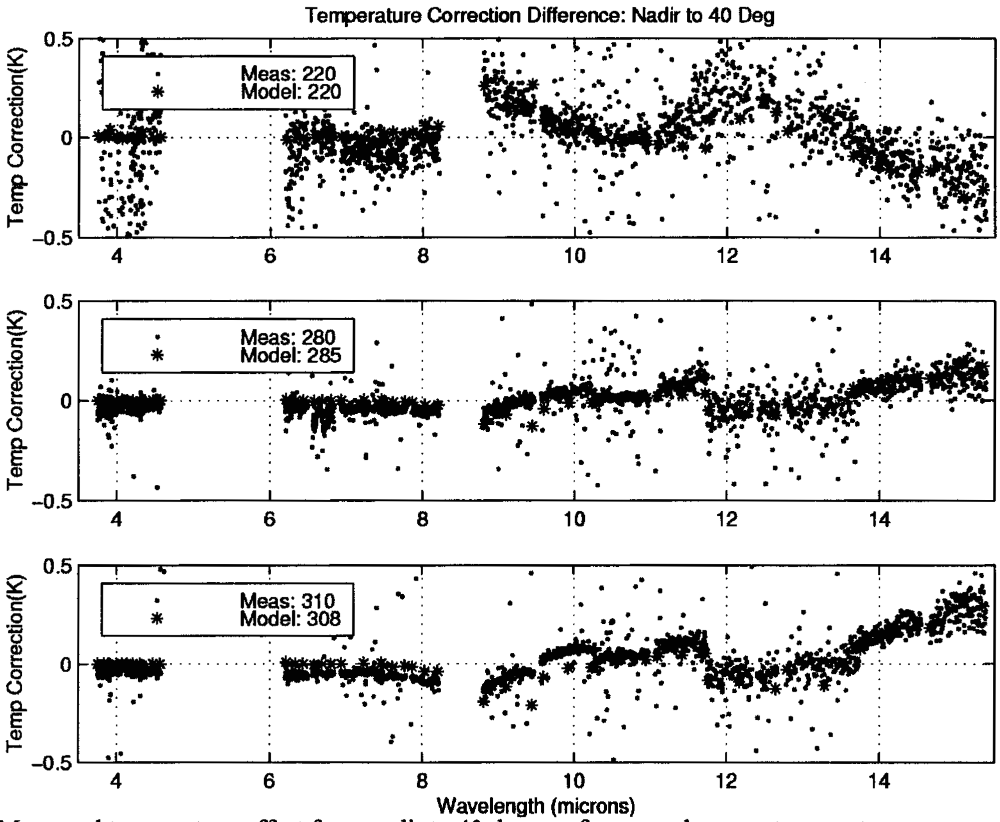

Figure 5. Measured temperature offset from nadir to 40 degrees for several source temperatures.

CALIBRATION RADIOMETRIC INTERCEPT

The LABB Stepped linearity test produces the AIRS calibration transfer curve at nadir. In this test the LABB is stepped in temperature from 205K to 310K and data obtained at each level. We obtain a set of LABB radiances from temperature sensors in the LABB and signals from the AIRS. We can fit the data to the standard polynomial equation

$$N = N_o + a_1\,(dn\text{-}dn_{sv}) + a_2\,(dn\text{-}dn_{sv})^2 \qquad (6)$$

The intercept, N_0, should be zero if there were no polarization since we are subtracting the background by viewing a cold space target. However, it is not zero, due to the difference in scan mirror polarization between the space view and earth view. Figure 6 shows the measured N_0 and the predicted radiometric offset due to polarization expected at nadir expressed in terms of temperature difference using equation 5. We see good correlation indicating that indeed the polarization is causing the offsets observed.

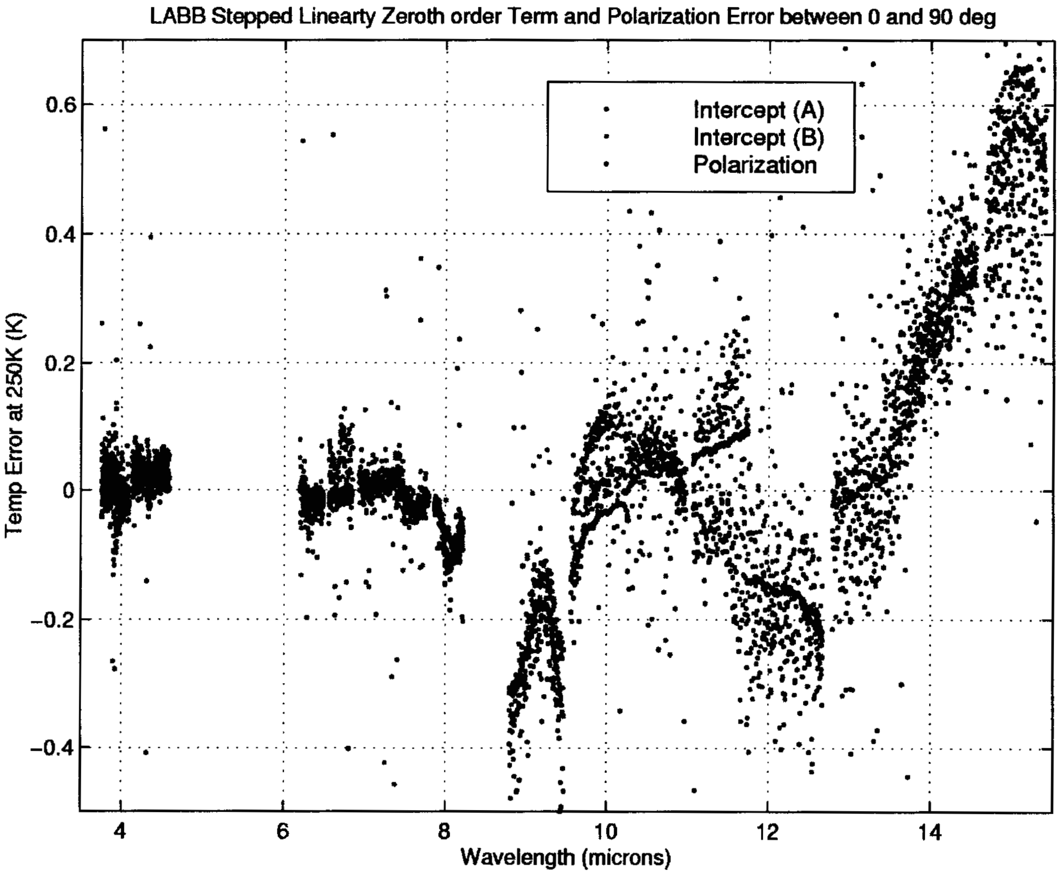

Figure 6. Intercept observed in fit to stepped linearity test is due to scan angle polarization effects.

FUTURE REFINEMENTS

The polarization phase of the AIRS spectrometer is expected to be small, however the measured data shows that it may not be zero. There are some difficulties in measuring the phase when the polarization is small. We are working to improve the fidelity of the model and measured data reduction algorithms to get a better handle on this term.

The correction terms observed at low temperatures follow the trend of the model, however there is a larger amount of scatter amongst the channels than desired due to low SNR. Also the deviation between the model and measurements is higher than desired in some wavelengths. Future refinements will be to tune the model for the input parameters (such as scan mirror temperature, emissivity, spectrometer polarization, etc.) to match these more sensitive cases at lower temperatures.

REFERENCES

1. "Development and test of the Atmospheric Infrared Sounder (AIRS) for the NASA Earth Observing System (EOS).", P. Morse, J. Bates, C. Miller, TBD
2. "AIRS instrument polarization response: measurement methodology, G. Gigioli and T. Pagano, SPIE 3759-30, July 1999
3. "Testing of mirror reflectance as a function of wavelength and polarization at varying angles of incidence", M.E. MacDonald, Sept 26, 1997, Project Report NOAA-16. Additional correspondance with Author in March 1999.